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Characterizing the Thermal Response of Fusible-Link Sprinklers

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Fire Research
Washington, DC 20234

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Final Report

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**CHARACTERIZING THE THERMAL
RESPONSE OF FUSIBLE-LINK
SPRINKLERS**

David D. Evans
Daniel Madrzykowski

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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CHARACTERIZING THE THERMAL RESPONSE OF
FUSIBLE-LINK SPRINKLERS

David D. Evans *
Daniel Madrzykowski

Abstract

Measurements of the thermal response of selected fusible-link sprinklers to sudden immersion into a hot gas flow are presented. Two methods of characterizing the response are detailed. One method explicitly accounts for phase change, the other does not. The methods are compared by using each to predict the response of a sprinkler to a selected mattress fire exposure.

Key Words: Fire extinguishment; fire models; fire protection; sprinkler heads; sprinkler systems; time constant

1. INTRODUCTION

The overall effectiveness of an automatic sprinkler system in suppressing an unwanted fire is dependent on the time it takes to respond to the fire condition. Common automatic sprinkler systems are activated by hot combustion products, transported from the source fire, which heat a thermal control element to a predetermined activation temperature. This temperature is usually associated with some part of the sensing element undergoing phase transition.

In the specific case of the common solder type sprinkler link each increment of energy transferred to the link from the fire in excess of energy losses raises the temperature of the link and binding solder

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materials until the solder begins to fuse. At this temperature most additional energy goes into completing the phase transition for the solder and not into raising the link temperature. When enough solder material has fused the link ruptures, activating the sprinkler head.

The predominant mechanism for heat transfer to a sprinkler link or other thermal sensor is by convection of hot combustion products. Heat transferred by radiation during the initial fire growth period is of secondary importance [1]¹. To predict the temperature of the thermal sensing element and the time at which activation conditions are reached, the thermal response characteristics of the sensor must be determined. A useful method to characterize the thermal response of a sprinkler linkage is to measure the temperature response of the link to sudden immersion in a hot gas flow.

2. EXPERIMENTAL APPROACH

2.1 Apparatus for Thermal Response Measurements

Characterizing the response time of sprinkler links by sudden immersion in a hot gas flow is the basis for the present Factory Mutual Research Corporation (FMRC) plunge test [1]. For this study, an apparatus not as refined as the FMRC plunge test but sufficient for the needs of this exploratory work was constructed.

Shown in figure 1, the apparatus consisted principally of a commercial heat gun to supply a forced hot air flow to an aluminum tube (114 mm ID) with a deflector plate across the entrance to help diffuse and mix the hot air flow. The gas temperature was measured continuously near the tube outlet with a thermocouple suspended in the flow. For

¹Numbers in brackets indicate the literature references at the end of this paper.

testing, sprinkler heads were placed in the supporting clamp at the exit of the tube. The clamp is arranged in such a way that the sprinkler head could be held outside the hot air flow prior to testing, but rapidly relocated into the center of the flow to initiate testing. Generally the linkage on the head being tested was placed as close as practical to the exit of the tube without resulting in appreciable blockage to the air flow. The nominal air flow velocity across the tube outlet was 2.13 m/s. The turbulence level in the flow, although known to affect the heat transfer ratio, was not measured. The gas outlet temperature could be varied by controlling the voltage applied to the heating coils with an exterior variable transformer. However, a simple air flow temperature of $90^{\circ}\text{C} \pm 4^{\circ}\text{C}$ was used for these tests. The aluminum tube wall was found to equilibrate at $60^{\circ}\text{C} \pm 4^{\circ}\text{C}$ under test conditions in the laboratory.

2.2 Sensing Element Instrumentation

Various methods of attaching thermocouple junctions to a fusible link in order to measure its temperature were examined. No method of attachment of a pre-welded junction to the face of the link proved mechanically rugged enough for testing. In order to instrument a link, two small holes were drilled opposite each other in the edge of the disk and fitted tightly with one wire of an AWG-24 pair of Type K thermocouple cable. The disk or link material formed the conducting path between these junctions. In an effort to minimize conduction of heat to the sensing element through the attached wires, each wire was left electrically insulated up to the junction and also mechanically formed to closely follow the edge of the link or disk. This method of instrumenting the links proved to be both mechanically rugged and repeatable without undue difficulty.

2.3 Measurements

The time response characteristics of three industrial sprinklers were measured. Sprinklers A, B, and C are shown instrumented, each with a thermocouple connected to its thermal link, in figures 2, 3 and 4. Each link had a labeled activation temperature of 74°C. Each sprinkler was tested oriented such that the broad side of the thermal link faced the upstream direction of the hot gas flow.

Figures 5, 6 and 7 show the temperature response of the three thermal linkages in response to sudden immersion in the hot air stream, the temperature of which is also recorded in the figures for the duration of the test.

In each plot the temperature of the link is seen to increase in response to the heat transferred from the hot air stream up to a point when the rate of temperature rise decreases abruptly. This abrupt change in rate of temperature increase, which forms a plateau in the time-temperature curve, indicates the onset of phase transition in the links. Rupture of the link is indicated by the termination of the temperature plot.

Focusing on figure 5, for sprinkler A, in the plateau region the temperature is not constant, but undergoes a gradual rise from 71°C to 74°C. This behavior was shown to be reproducible in several tests. The change in link temperature during solder fusion may indicate that the sample of solder material tested was not a true eutectic mixture, or possibly experienced non-isothermal conditions during the testing.

The fusion characteristics of the solder material used in sprinkler A were investigated with separate differential scanning calorimeter (DSC) measurements. Data from the scan is presented in figure 8 in units reflecting apparent heat capacity of the sample. For the purposes here, it is only necessary to note that melting in the solder material

is not completed at a single temperature but has two distinct peaks. Very little energy is associated with the second peak near 74°C compared with the lower temperature phase transition peaking at 67°C. This DSC data for the solder material would suggest a temperature response as measured for sprinkler link A (figure 5); a plateau region representing the low temperature phase transition, a slight temperature rise to the second phase transition of short duration before link rupture. It should be observed that even though the qualitative features agree, the plateau in the response curve for sprinkler A (figure 5) is at approximately 72°C while a range of 63°C to 67°C was suggested by the low temperature transition from the DSC measurements (figure 8). The reason for this discrepancy is presently unknown.

3. DISCUSSION OF MEASUREMENTS

3.1 Energy Transfer

An interesting parameter that characterizes one aspect of the sprinkler link response is the fraction of energy needed to fuse enough solder to rupture the link, compared to the total energy needed to heat the link from ambient to rupture temperature. Ignoring the effects of radiative heat transfer between the link and the surroundings and conductive heat transfer with the sprinkler body, estimates of the above energy ratio can be calculated from the information in figures 5, 6, and 7.

The convective heat transferred to the link from the hot air stream is proportional to the area between the outlet air temperature curve shown in figures 5, 6 and 7 and the respective link temperature curve. Figure 9 shows the two areas of interest for sprinkler A. The fraction of energy involved with link fusion is

$$= \frac{\text{fusion energy}}{\text{rupture energy}} = \frac{\text{Area A}}{\text{Area (A + B)}} \quad (1)$$

For sprinklers A, B and C, this fraction of the energy associated with the phase transitions in the solder, compared to the energy to rupture the link from the respective 24.2°C, 29.2°C, and 27.4°C, initial temperatures were: 0.26, 0.31, and 0.088 respectively. Sprinkler C, which had the shortest time to rupture, or overall fastest response, also had the lowest ratio of fusion energy compared to total rupture energy.

3.2 Models of Time Response

The laboratory measurements made on the sprinkler heads established the activation time for the linkage when exposed to a particular controlled hot gas flow. To predict the activation of the same linkage under different gas velocity and temperature conditions a dynamic model for the thermal response must be formulated. Two simple models will be discussed.

3.2.1 Single Parameter Model

In the simplest model, the thermal response of the sprinkler linkage is characterized by a single parameter τ , usually referred to as a time constant. This time constant has its basis in a simple model of the heat transfer process to the link. As discussed by Heskestad and Smith [1], the equation governing the temperature-response of the sprinkler link up to the temperature at which phase transitions begin is:

$$d(\Delta T_{\ell})/dt = \tau^{-1}(\Delta T_g - \Delta T_{\ell}) \quad (2)$$

where ΔT_{ℓ} is the excess temperature of the link above the initial temperature, and ΔT_g is the excess temperature of the gas above the initial link temperature. The time constant, τ , may be related to the properties of the sprinkler linkage and the gas flow for convection dominated heat transfer according to:

$$\tau = MC/h_c A \quad (3)$$

where M is the mass, C is the specific heat, A is the area of the link exposed to gas flow, and h_c is the convective heat-transfer coefficient. The value of h_c and thus τ is dependent on the gas flow velocity passing over the link.

When the fusible link reaches the temperature at which phase transitions in the link solder begin, the temperature of the link remains nearly constant and is no longer predicted by equation 2. However, an overall time constant τ , that includes both the effects of thermal capacity and phase transitions in the linkage at a given gas flow velocity, is a useful quantity to calculate.

Equation 2 may be solved for conditions that are appropriate to model the test measurements made in this study, namely $\Delta T_\ell = 0$ at $t = 0$ and ΔT_g is a constant. For these conditions, ΔT_ℓ as a function of time found from equation 2 is

$$\Delta T_\ell = \Delta T_g (1 - e^{-t/\tau}) \quad (4)$$

By simply measuring the time to link rupture, t_r , in response to sudden immersion in a hot gas flow and calculating the excess activation temperature, $\Delta T_{\ell a}$, the rupture temperature of the link either measured or value indicated on link minus the initial temperature of the link, an overall value for the time constant may be determined. In this study this overall time constant will be labeled τ_1 . From equation 4 its value is:

$$\tau_1 = - t_r / \ln (1 - \Delta T_{\ell a} / \Delta T_g) \quad (5)$$

If the data for the link temperatures shown in figures 5, 6 and 7 are re-plotted in the form

$$\ln (\Delta T_g - \Delta T_\ell) \text{ vs. } t \quad (6)$$

then from equation 4 the slope of the curve will be, $-1/\tau$. Figures 10, 11 and 12 show a re-plotting of the data from figures 5, 6 and 7 respectively as solid lines. From equation 5 the value, $-1/\tau_1$ equals the slope of the straight line (shown as broken lines in figures 10, 11 and 12) connecting the first data point at time, $t = 0$ and the last data point at link rupture. Thus the overall time constant τ_1 may also be determined graphically.

This simple one parameter model for characterizing the thermal response of the sprinkler linkage can be used effectively to predict activation times, as will be discussed later, even though fusion of the link solder is not explicitly modeled and deviations from the measured temperature response are sometimes large. The method has an advantage over the two parameter model, which will be discussed next, in that the overall time constant, τ_1 , may be determined without measuring the link temperature history. Only the initial link temperature (room temperature), time to link rupture in hot gas flow, and rupture temperature (link activation temperature) are needed to determine, τ_1 .

3.2.2 Two Parameter Model

The single parameter model described in the previous section is the simplest characterization of the thermal response of the sprinkler linkage. As can be easily seen from figures 10, 11 and 12, there is a large deviation of the modeled link temperature compared to the measured values. A better correspondence between measured and predicted link temperature may be obtained from a two parameter model. For the two parameter model, a time constant, τ_2 , is used to characterize the response of the link up to the time of phase transition. Another constant is introduced to characterize the time delay from the onset of phase transition to link rupture.

To determine the two parameters for the model, two times must be measured. As with the one parameter model, the time to link rupture, τ_r , is needed. In addition, from plots of the experimental data such

as the solid lines in figures 10, 11 and 12, the time of an abrupt change in slope, t_p , signifying the onset of phase transition is needed. As with the single parameter model, a time constant, τ_2 , can be calculated using equation 5 with t_r replaced by t_p . Thus

$$\tau_2 = - t_p / \ln (1 - \Delta T_{la} / \Delta T_g) \quad (7)$$

The slope of the straight broken line from the initial data point continuing to time t_p as shown in figures 10, 11 and 12, for the sprinklers tested, is equal to $-1/\tau_2$. The temperature at which this line terminates, at time t_p , corresponds to activation temperature of the link.

The time delay from the onset of phase transition to link rupture, $t_r - t_p$ is determined from the experimental data. The temperature of the link during this time interval is modeled as constant at the activation temperature. This corresponds to the horizontal broken line in figures 10, 11 and 12.

This time delay itself is not a useful parameter for modeling the sprinkler response, because it will vary with the rate of heat transfer to the linkage. Applying the convective heat transfer analysis, a total energy transfer to the link during the time interval t_p to t_r can be determined. This change in link energy associated with melting enough solder in the link to cause rupture, is likely to be insensitive to heat transfer rate. In the two parameter model this change in link energy, ΔE , will be considered a parameter for the link.

Incorporating the simplification of the two parameter model, the temperature of the link is constant over the time period from the onset of phase transition to link rupture. Therefore the convective energy transfer to the link during this time interval is:

$$\Delta E = hA(\Delta T_g - \Delta T_{la})(t_r - t_p) \quad (8)$$

The quantity hA is determined from τ_2 , thus equation 8 becomes:

$$\Delta E = MC \left[\frac{1}{\tau_2} (\Delta T_g - \Delta T_{la}) (t_r - t_p) \right] \quad (9)$$

The quantity $\Delta E/MC$ can be determined from the experimental data and is a parameter for the linkage.

3.2.3 Model Parameters Determined from Tests

In addition to the values of the parameters characterizing the response curves being indicated on figures 9 through 14, tabulated values of experimental measurements and calculated parameters for the three sprinklers are given in table 1.

Table 1
Test Results and Model Sprinkler Time Response Parameters

Sprinkler	$T_o,$ °C	$T_g,$ °C	$T_{la},$ °C	$t_p,$ sec	$t_r,$ sec	$\tau_1,$ sec	$\tau_2,$ sec	$\Delta E/MC$ °C
A	24.2	87.9	73.2	118	194	132	80.5	13.9
B	29.2	93.7	76.7	103	182	136	77.2	17.4
C	27.4	89.0	72.3	89	106	81.2	68.2	4.16

3.2.4 Radiation and Conduction Effects

The analysis of data for thermal response of the sprinkler links developed in sections 3.2.1 and 3.2.2 assumes that the heat transfer to the links is dominated by convection. Radiation and conduction heat transfer to the link are not considered in the analysis. The time response characteristics of a machined brass disk similar in size and geometry to common fusible links was studied under the same test conditions as used for the sprinkler measurements. These measurements form a basis for qualitative discussion of radiation and conduction effects in the test apparatus.

Figure 13 shows the polished brass disk suspended within a ring by cotton threads. In this configuration radiation heat transfer between the disk and the surroundings have been minimized by polishing the disk. Conduction heat transfer between the disk and the metal support is minimized by suspension of the disk with long cotton threads. Heat transfer to the disk in this configuration should be dominated by convection. Heat transfer to the disk from a constant temperature and constant velocity air flow is characterized by a constant convective heat transfer coefficient, h_c . From equation 4, the value of the time constant, τ , will consequently be constant, and the slope of the thermal response data on a plot of $\ln(\Delta T_g - \Delta T_L)$ vs. time from equation 5 will be a straight line.

Figure 14 shows the test data for the polished brass disk suspended in the ring holder. This data falls along a straight line, indicating that as initially assumed, in this apparatus convection alone is the dominate mode of heat transfer to this disk. The slope of the straight line indicates that the disk has a time constant of 97 seconds. Also indicated on the graph is the point at which the disk temperature reached 74°C. Normally this would be the termination point of common fusible link tested.

Blackening the surfaces of the disk with a coating of carbon black, and retesting it in the apparatus provide a set of response data in which radiative heat transfer between the disk and its surroundings is favorable. Figure 15 shows that under these conditions, the response data no longer forms a straight line as in figure 14. As the disk increases in temperature, the data bends away from the initial straight line which had a slope equivalent to a time constant of 97 seconds. The change in slope of the data indicates a gradual increase in the time constant for the disk. This apparent increase in time constant is the result of heat loss from the disk to its surroundings by radiation.

From the data in figure 15, which represents favorable conditions for radiative heat loss in the apparatus, an estimate of the expected influence of radiation in the test data for sprinklers A, B and C may be obtained.

The blackened disk reached 74°C in 159 seconds. Using equation 5, with an initial temperature of 20.3°C and gas temperature of 91.8°C , the time constant for the disk would be calculated as 114 seconds. This differs by only 18 percent from the value of 97 seconds based on the initial slope of the curve. The influence of radiative transfer could be further minimized by increasing the temperature of the gas flow and thereby increasing the dominance of the convective component of heat transfer.

When the sprinkler link is installed in the body of the sprinkler heat transfer between the body and the link by conduction can influence the time constant of the link. For completeness, the polished brass disk, already shown to minimize radiative heat transfer, was mounted in place of the fusible link in a modified link and lever sprinkler body as shown in figure 16.

This installation was tested. The response data is presented in figure 17. The initial slope of the curve indicates that the installation of the brass disk in the sprinkler body has increased its time constant to 119 seconds from the previous value of 97 seconds. The increase in time constants indicates the disk is losing heat by conduction to the sprinkler body, which because of its larger mass does not heat as fast as the link in the hot air flow.

4. USE OF THE MODELS

Each of the two models presented to characterize the response time of sprinklers can be used to predict the activation time for sprinklers given the air temperature and velocity history of the fire gases passing

the sprinkler head. This type of prediction has been done previously by Alpert [2] using the one parameter model. Of particular interest in this study is the comparison of the differences between the predicted activation times in response to given fire conditions for the one and two parameter models. Using data for the air temperature just below the center ceiling from a test in which a polyurethane mattress was burned in a 3.35 m x 4.22 m x 2.35 m height room, predictions of the activation time based on the two models of sprinkler response may be made.

Although it is known that both the temperature and velocity of the air flow past a sprinkler influence its response time (Alpert [2]), for the purpose of comparing the two response models velocity variation will be neglected. For simplicity the velocity of the air flow will be assumed constant and equal to the value used in the test apparatus, 2.13 m/s.

Figure 18 shows a plot of ceiling layer gas temperature vs. time for the initial growth period of a typical mattress fire [3]. From this given gas temperature history, the activation time of each of the three sprinklers tested, A, B and C using both the one and two parameter models may be predicted. Using the one parameter model calculation of the activation time is straight forward. Equation 2 may be integrated numerically for ΔT_g as a function of time following a Runge-Kutta procedure [4] using values of ΔT_g determined from figure 18 at five second intervals, and measured time constant τ_1 for the sprinkler of interest. The time at which the predicted link temperatures reach the value of activation temperature measured in the laboratory test, (approximately 74°C for the sprinkler examined in this study) is the predicted activation time.

Using the two parameter model, link temperatures up to the activation temperature are predicted as above with time constant τ_2 replacing τ_1 . In this case activation is delayed by the time necessary

to transfer heat used in fusing the material, $\Delta E/MC$ from equation 7. Activation occurs when the critical value of $\Delta E/MC$ is reached, which for the case of non-constant gas temperature is slightly more complicated than equation 9 and requires an integration over time of:

$$\Delta E/MC = \frac{1}{\tau_2} \int_{t_p}^{t_r} (\Delta T_g - \Delta T_{la}) dt \quad (10)$$

Table 2 presents the results of calculations for predicted activation of each of the three sprinklers evaluated using the two models. Predicted activation times using the single parameter model span a range of 34.3 seconds, from 216.6 for sprinkler C to 250.9 for sprinkler B. This reflects the faster response of an 81.2 second time constant, (τ_1), sprinkler compared to a 136 second sprinkler. In all cases the two parameter model predicts a shorter activation time. The difference is a slight 1.6 seconds for sprinkler C, and a greater 8.2 seconds and 8.7 seconds for sprinklers A and B respectively.

Table 2

Predicted Activation Time for Pendent Sprinklers in Mattress Fire

Sprinkler	Activation Time (Seconds)		
	A	B	C
One parameter model	243.2	250.9	216.6
Two parameter model	235.0	242.2	215.0

As would be expected, when the effects of phase transitions represent only a small part of the response characteristic (figure 12) of the sprinkler as in the case of sprinkler C, the one and two parameter models predict almost identical activation times, 216.6 seconds and 215.0 seconds respectively. For sprinklers A and B, the effects of phase transition are more pronounced (figures 10 and 11) and differences

in predicted activation times of slightly more than 8 seconds occur in response to the selected mattress fire (figure 18). Overall, the differences in predicted activation times noted above are within the expected accuracy of either model, as well as the degree of repeatability of thermal response between different specimens of the same model sprinkler.

5. CONCLUSIONS

Measurements performed have shown that for selected fusible link sprinklers, the amount of energy associated with fusion of the link can be as much as 31 percent of the total energy transfer needed to rupture a link which was initially at room temperature.

Using measurement of the link temperature response to sudden immersion in a hot gas flow, two simple models can be formulated to represent the thermal behavior. When used to predict sprinkler activation time in selected fire conditions, the models produce slightly different results. The difference is, however, within the expected accuracy of the predicted method and repeatability of the sprinkler hardware.

Radiation effects in the present laboratory measurement could increase measured time constants by as much as 18 percent under worst case conditions. Conduction through link arms in one sprinkler design increase the measured individual link time constant by 23 percent.

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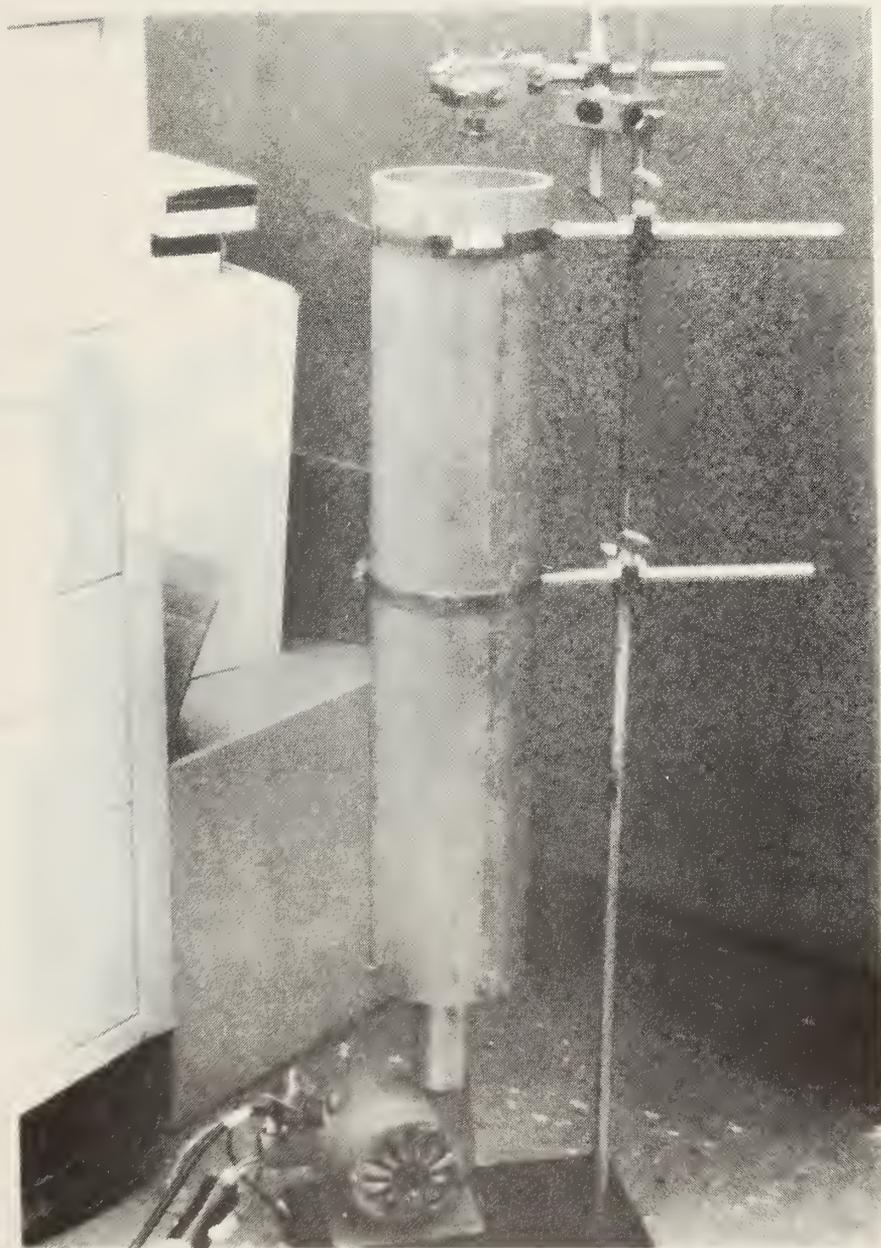


Figure 1. Thermal response measurement apparatus

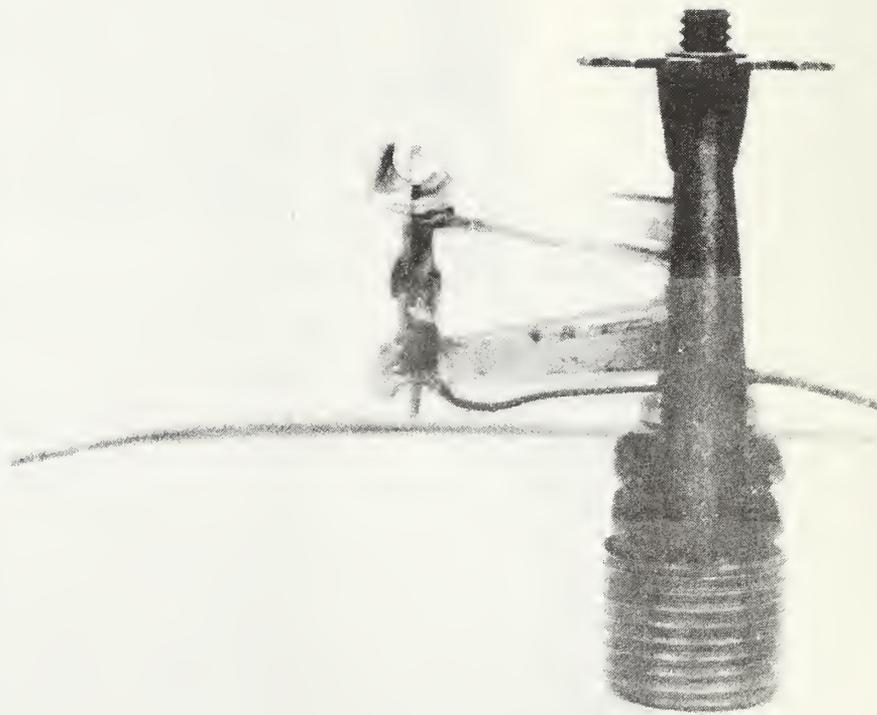


Figure 2. Instrumented sprinkler A



Figure 3. Instrumented sprinkler B

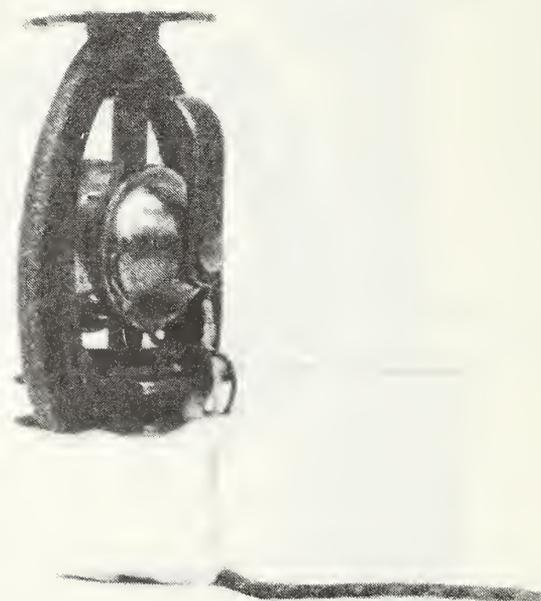


Figure 4. Instrumented sprinkler C

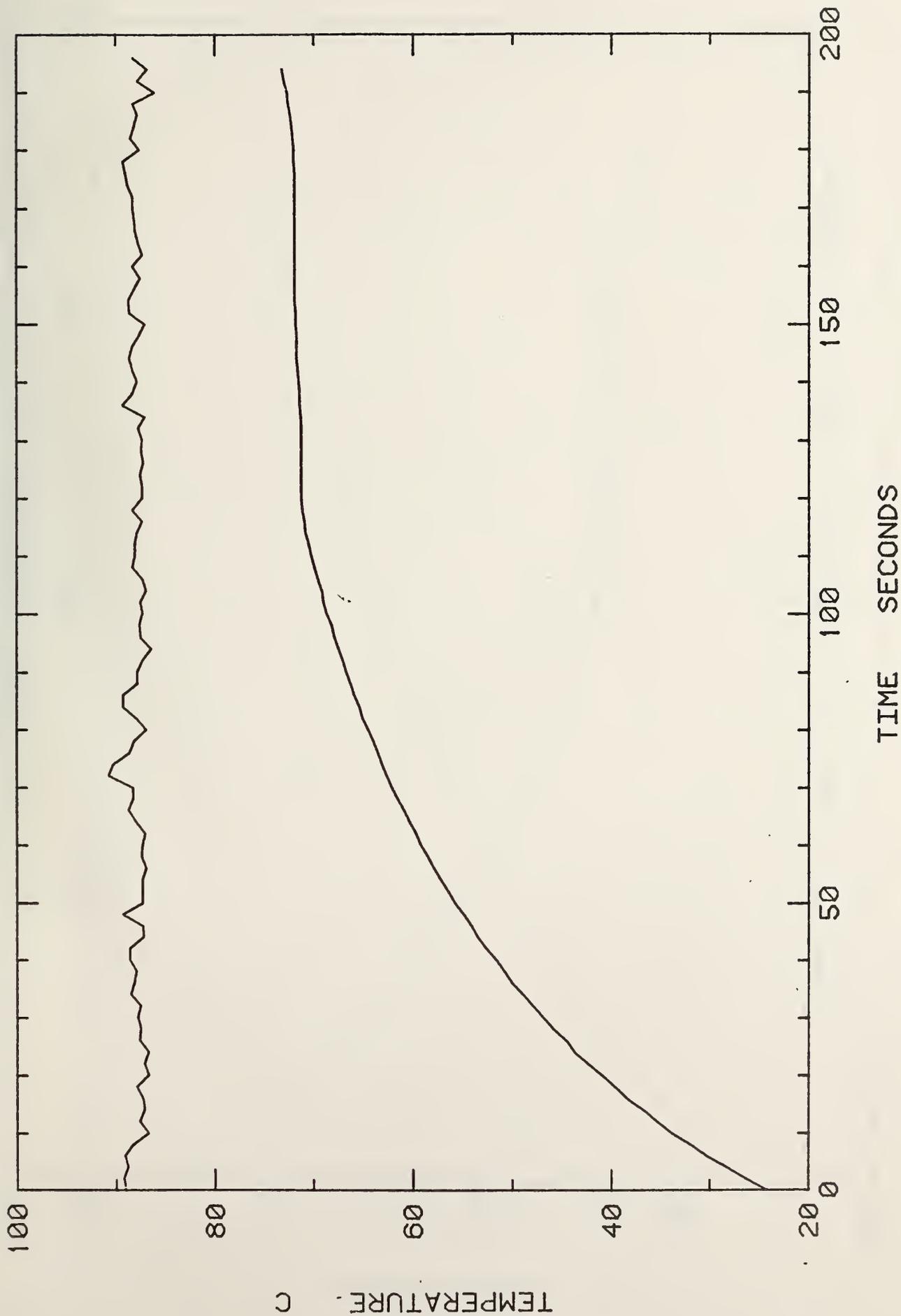


Figure 5. Sprinkler A, test link and gas temperatures

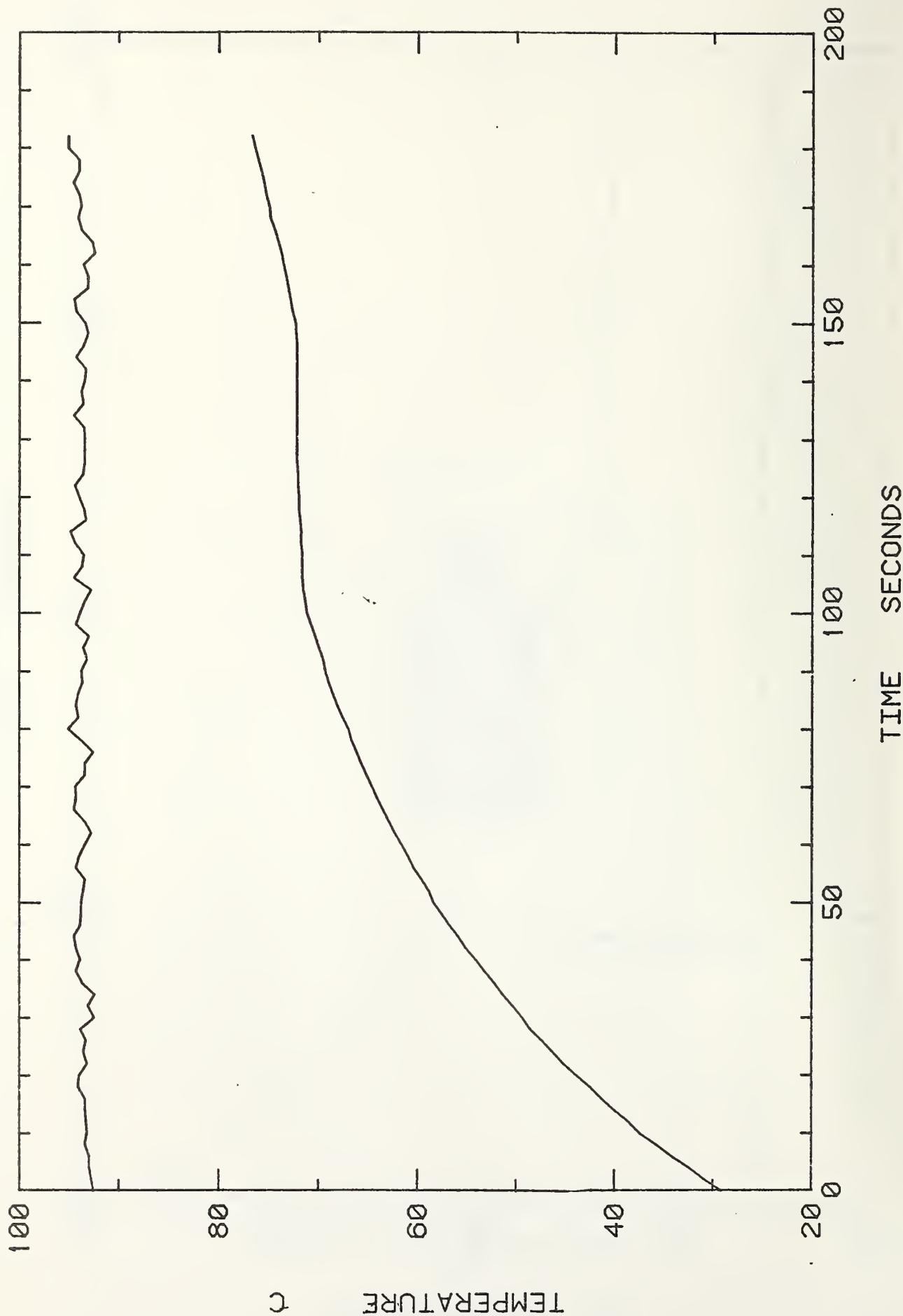


Figure 6. Sprinkler B, test link and gas temperatures

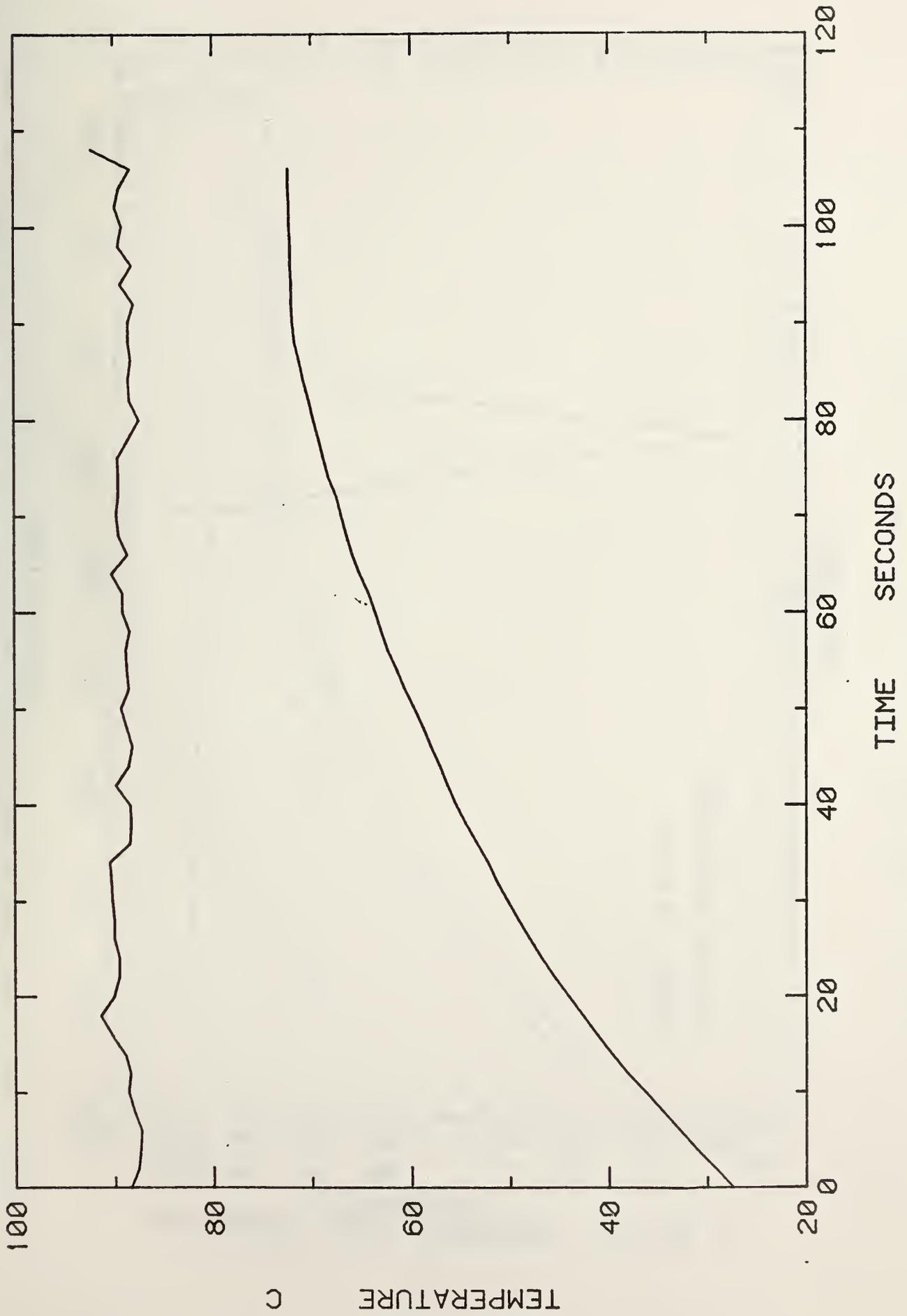


Figure 7. Sprinkler C, test link and gas temperatures

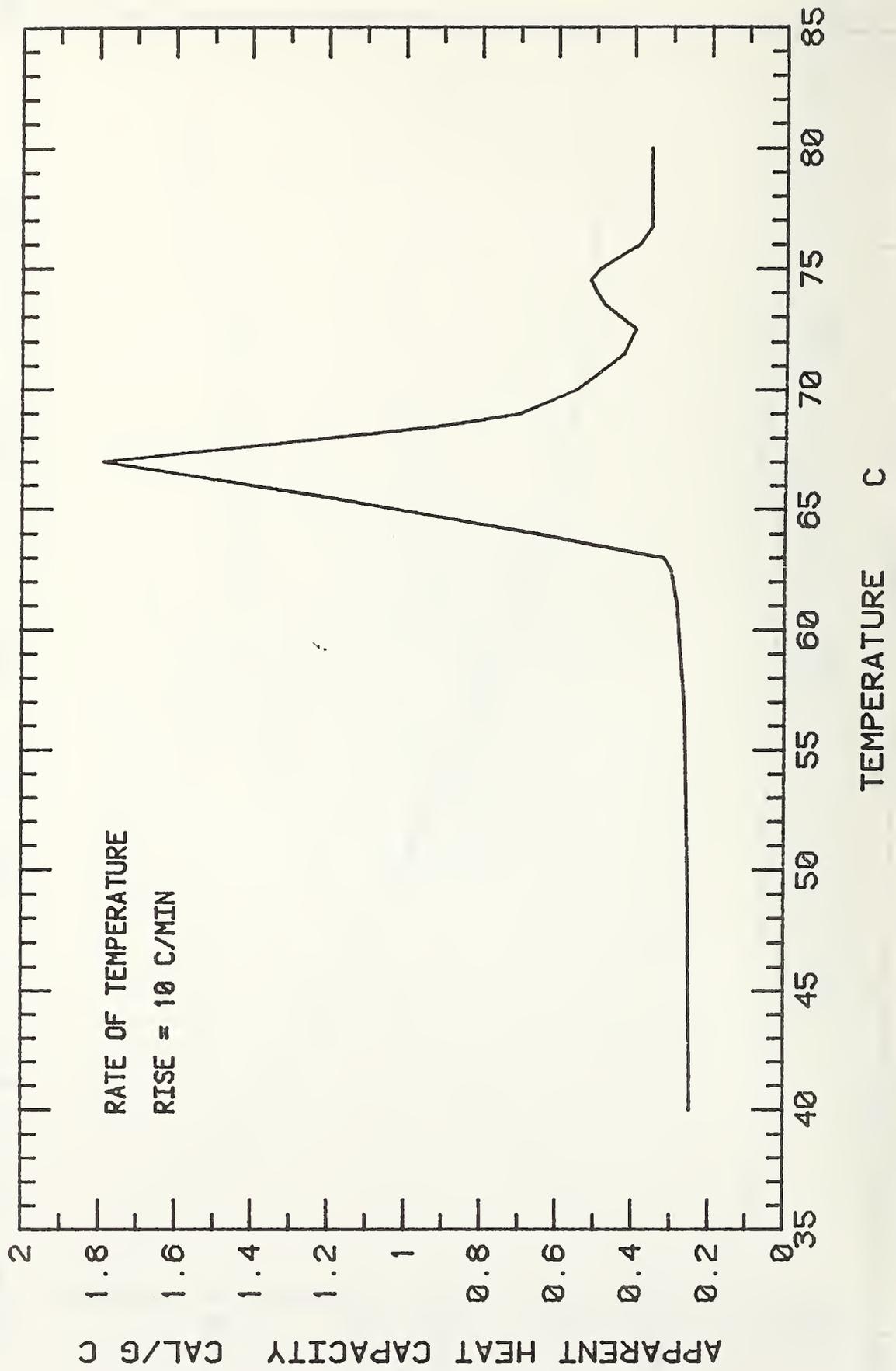


Figure 8. Apparent heat capacity of sprinkler A link solder material

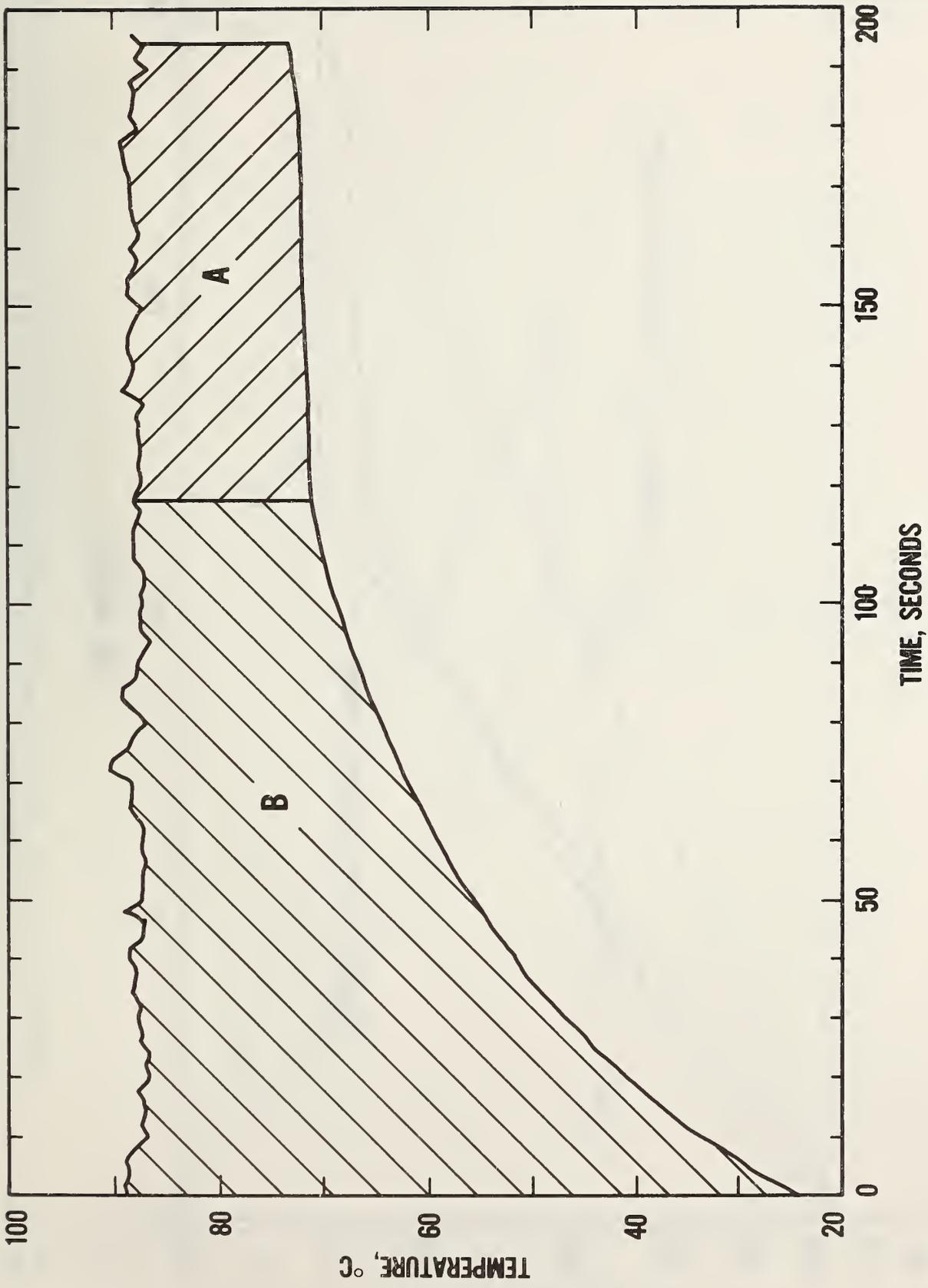


Figure 9. Areas associated with energy transfer, sprinkler A

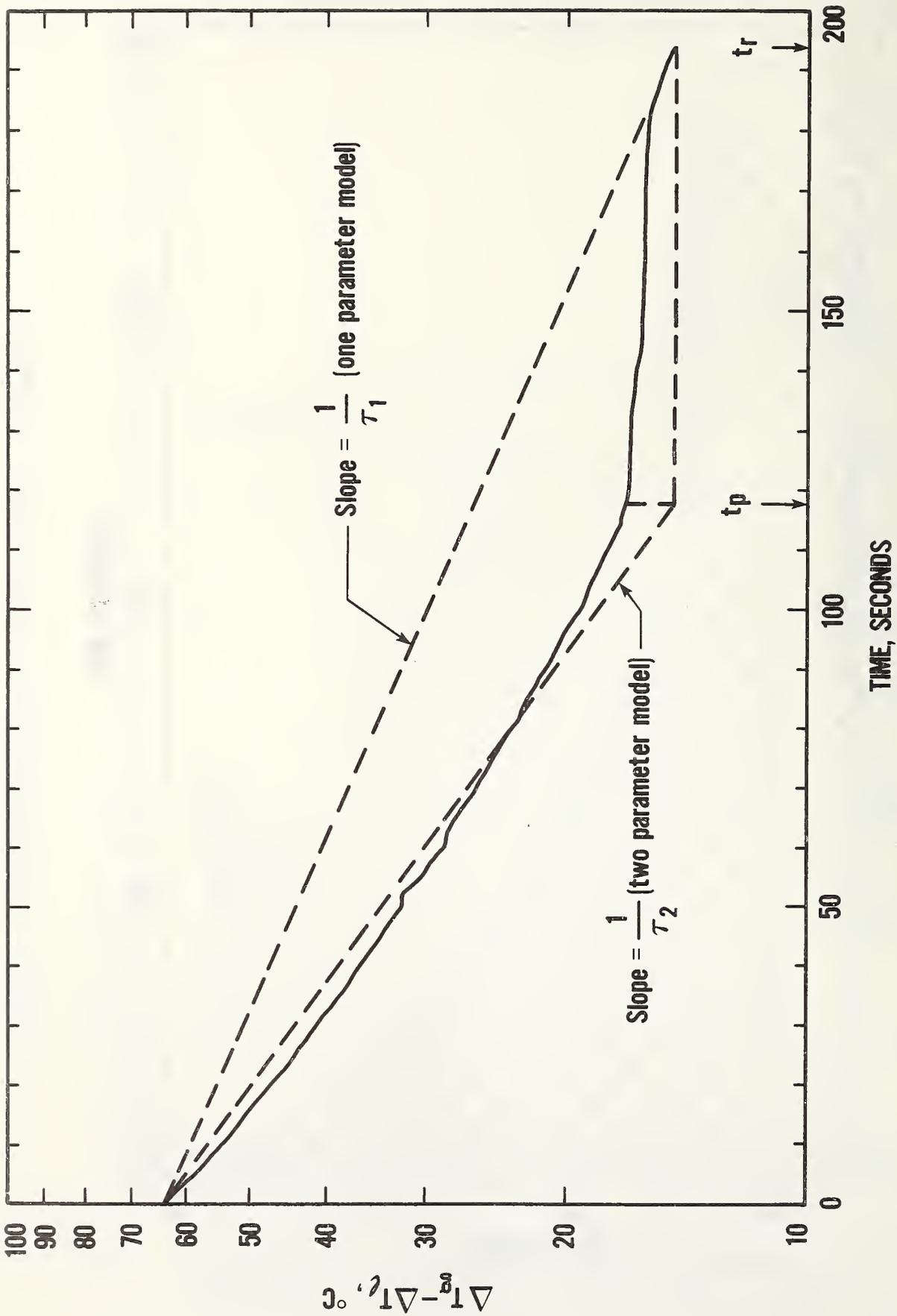


Figure 10. $\ln(\Delta T_g - \Delta T_a)$ vs time for sprinkler A

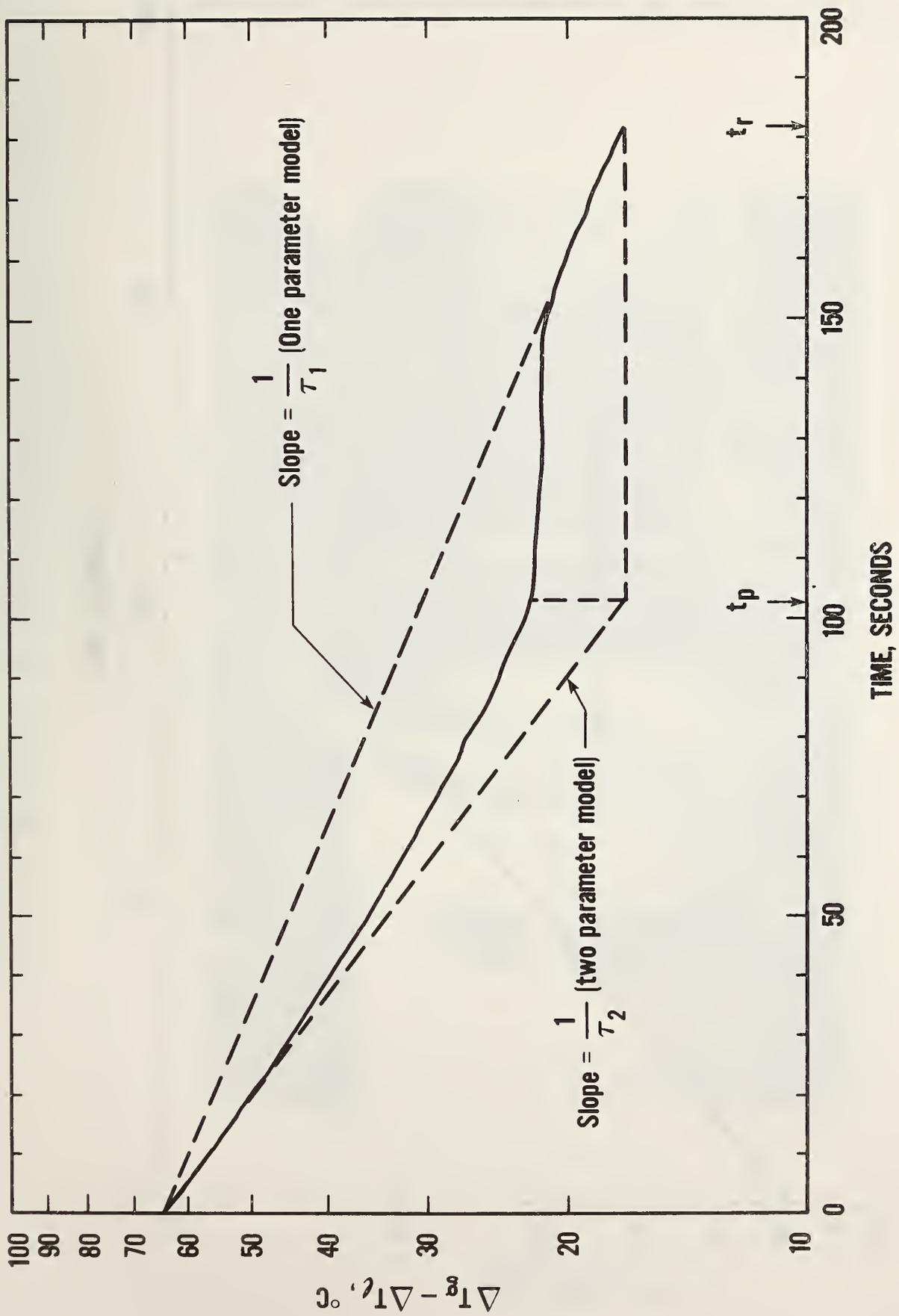


Figure 11. $\ln(\Delta T_g - \Delta T_0)$ vs time for sprinkler B

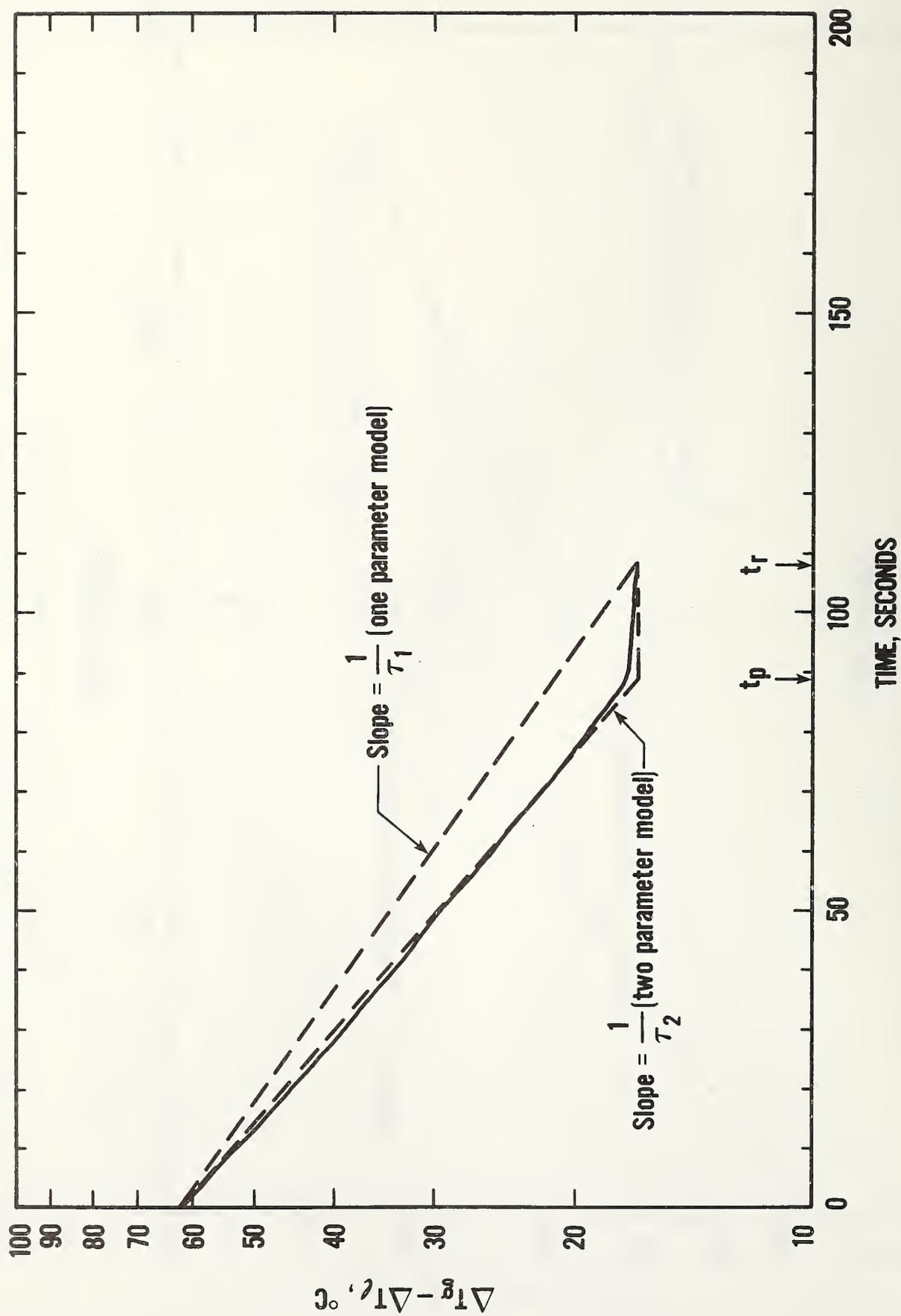


Figure 12. $\ln(\Delta T_g - \Delta T_{g,c})$ vs time for sprinkler C

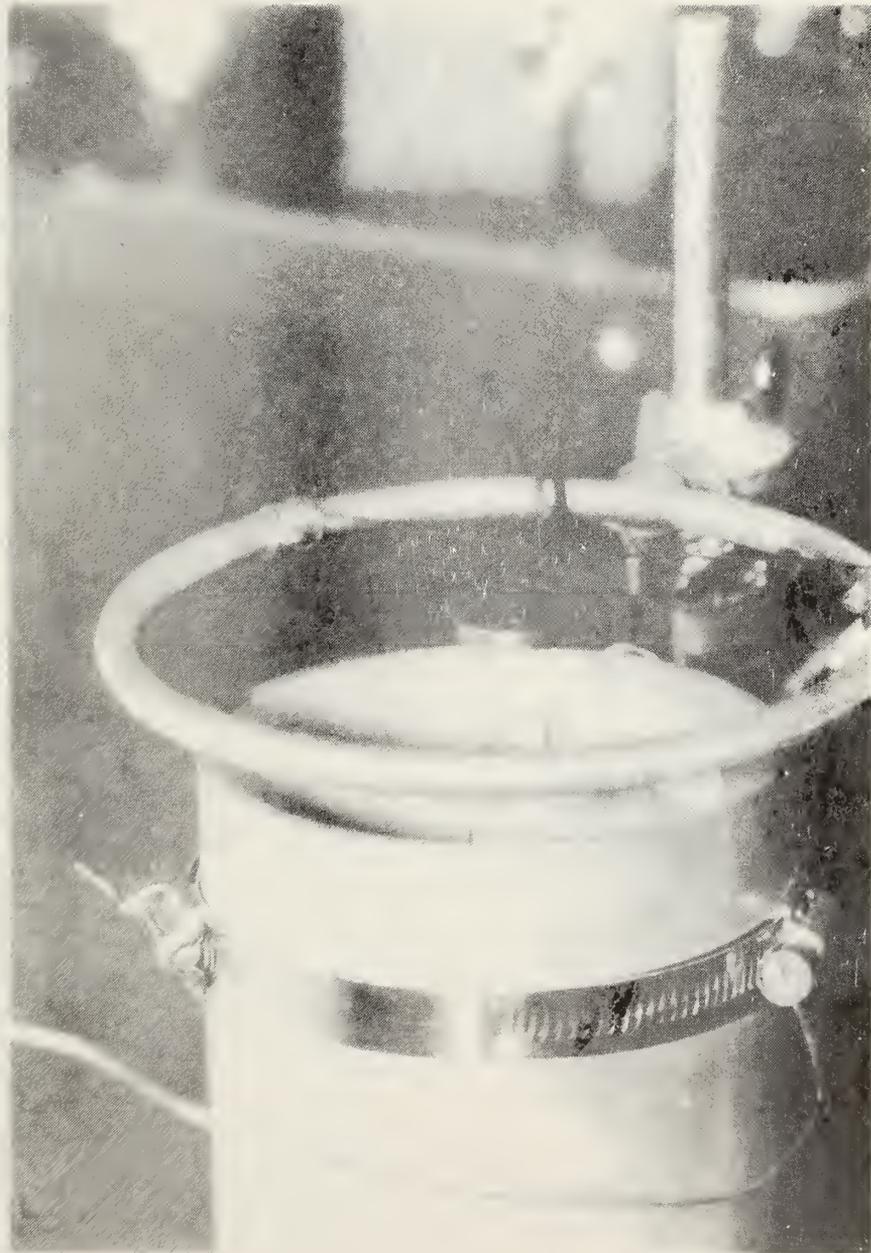


Figure 13. Polished brass disk

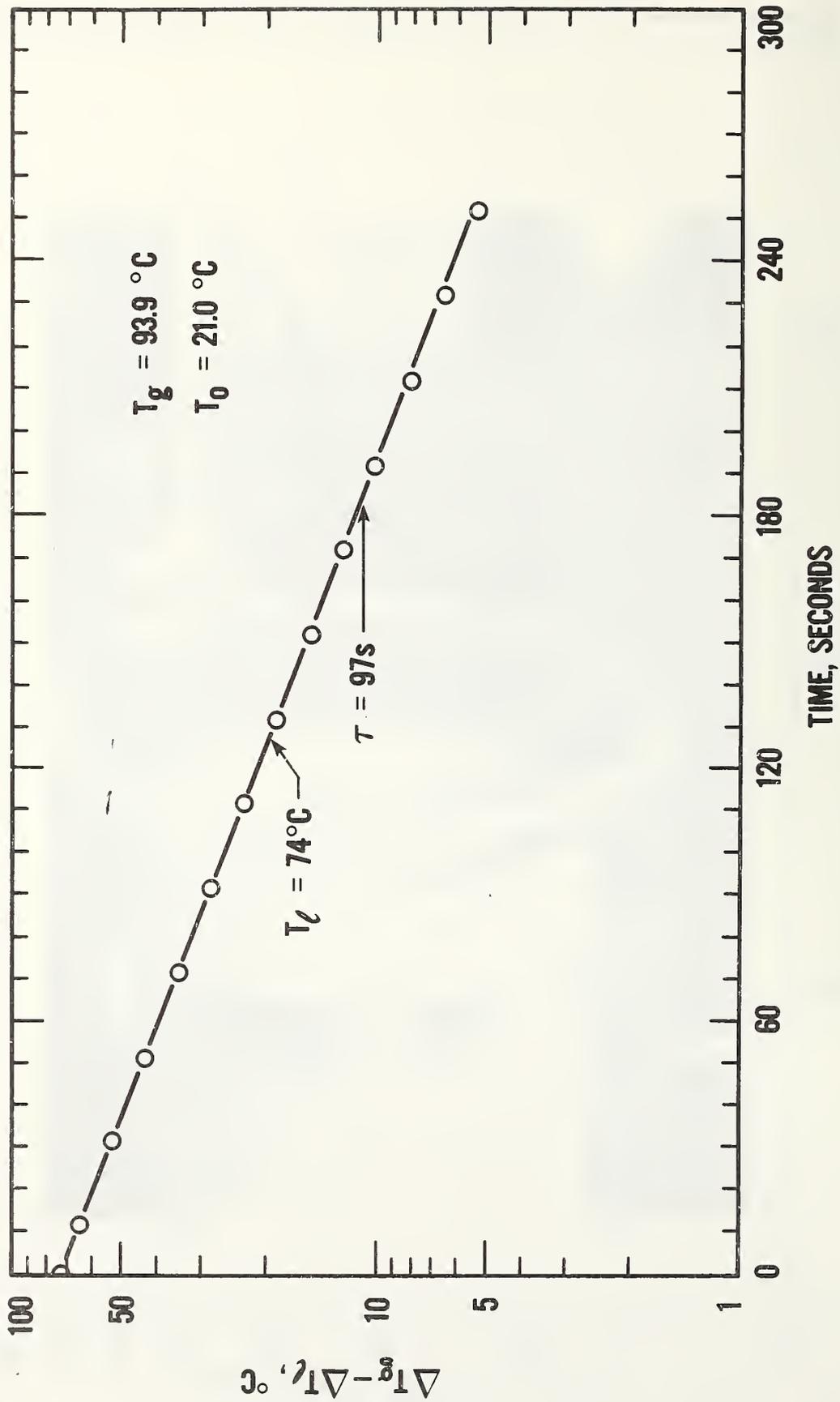


Figure 14. $\ln (\Delta T_g - \Delta T_l)$ vs time for polished brass disk

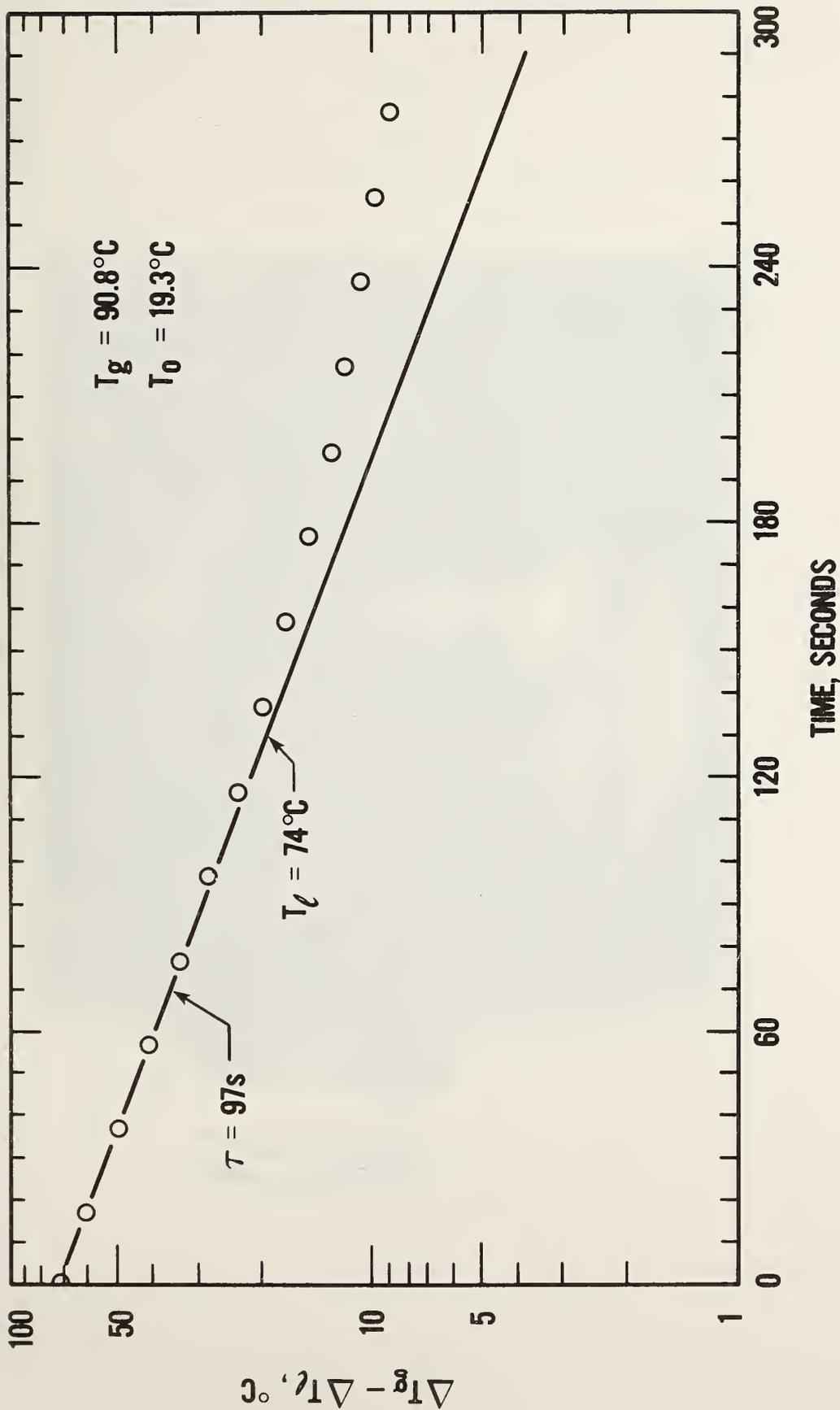


Figure 15. $\ln(\Delta T_g - \Delta T_l)$ vs time for black brass disk

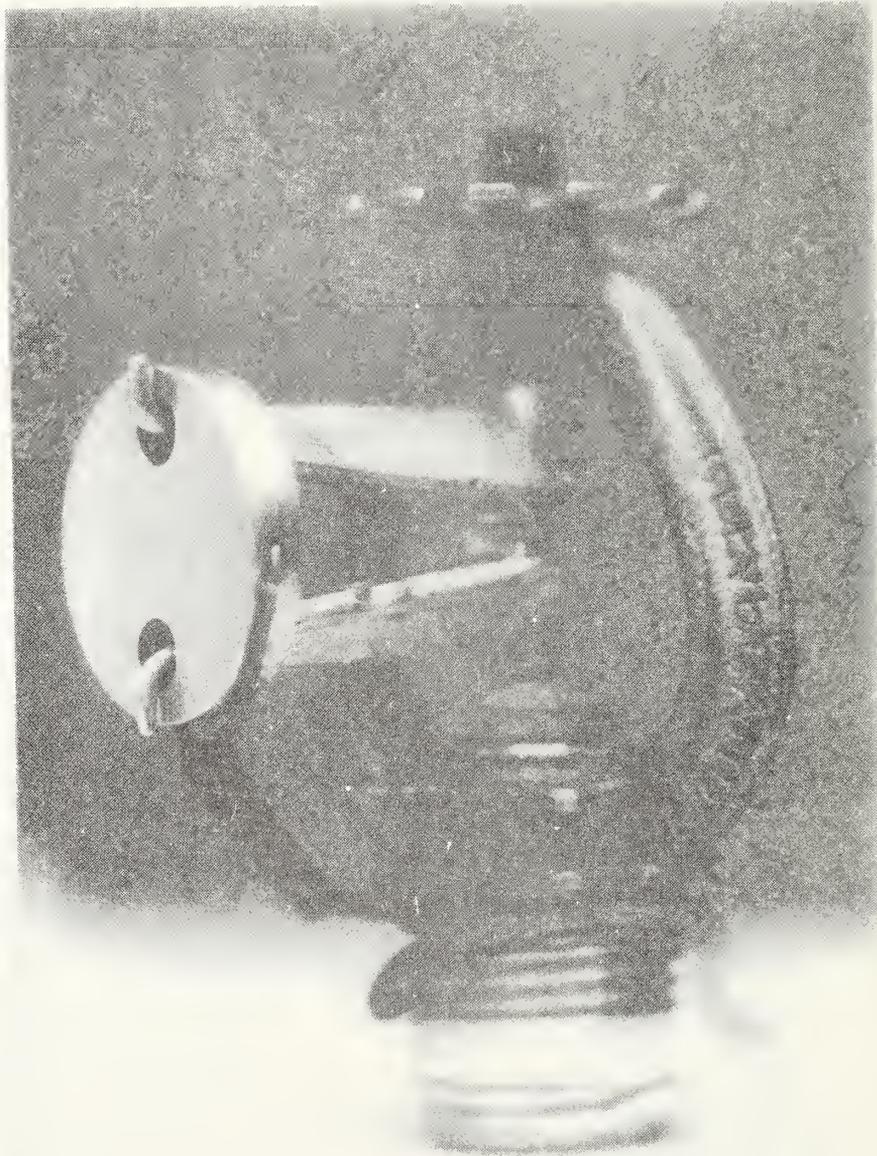


Figure 16. Brass disk mounted in sprinkler body

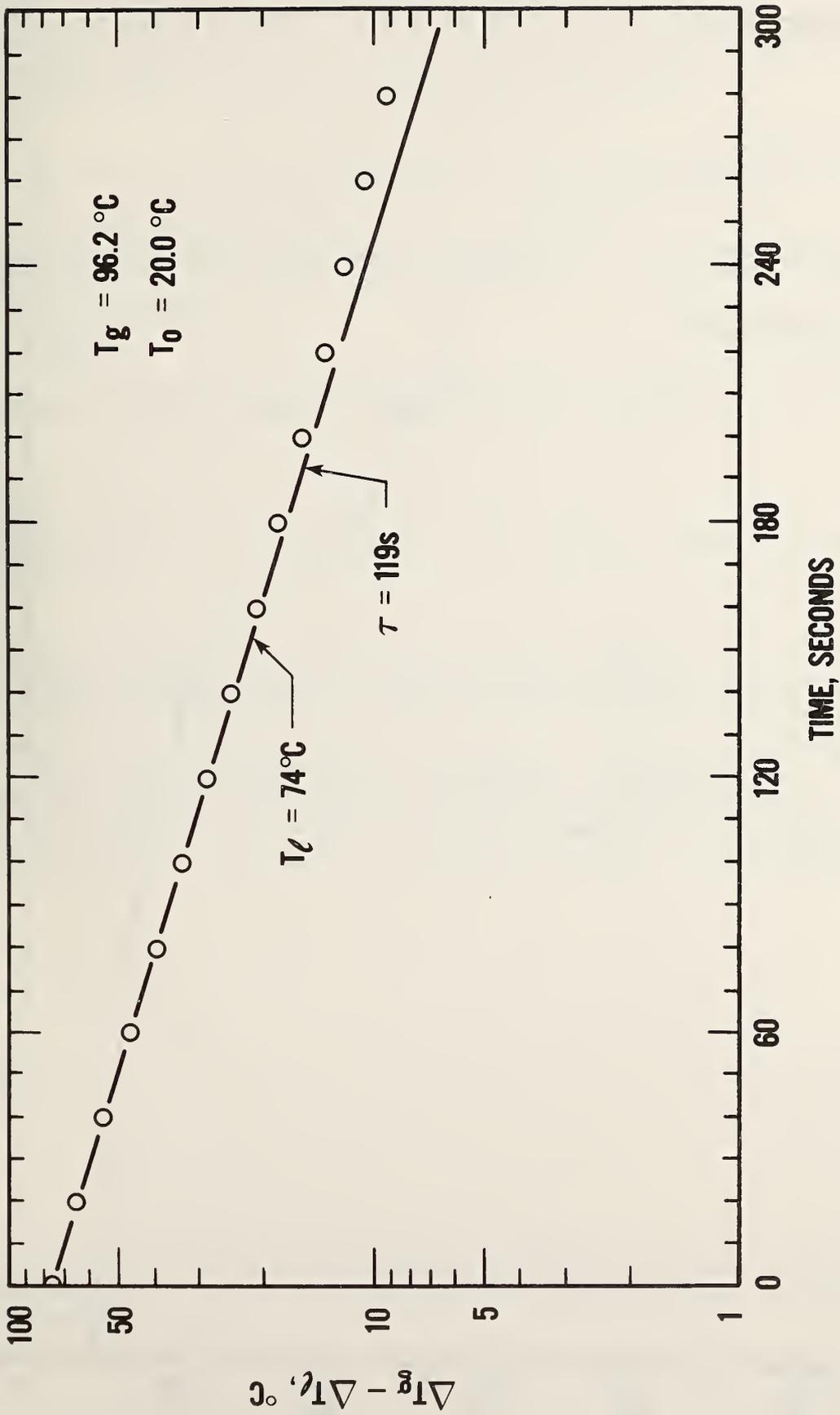


Figure 17. $\ln(\Delta T_g - \Delta T_l)$ vs time for polished brass disk mounted in sprinkler body

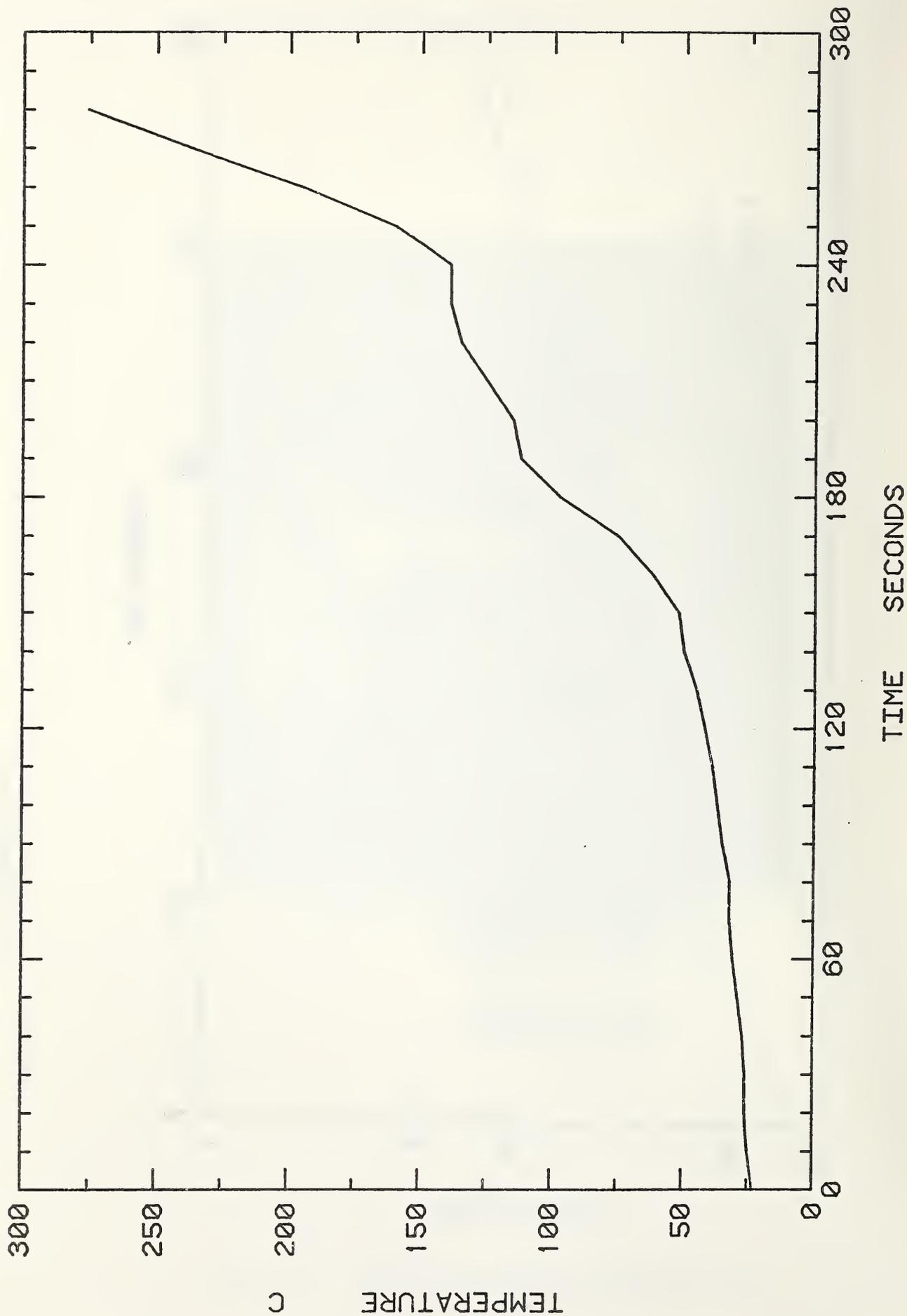


Figure 18. Ceiling layer gas temperatures for mattress fire

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11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here) Measurements of the thermal response of selected fusible-link sprinklers to sudden immersion into a hot gas flow are presented. Two methods of characterizing the response are detailed. One method explicitly accounts for phase change, the other does not. The methods are compared by using each to predict the response of a sprinkler to a selected mattress fire exposure.			
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